KEPLER MISSION: A MISSION TO FIND EARTH-SIZE PLANETS IN THE HABITABLE ZONE

William J. Borucki[1], David Koch[2], Gibor Basri[3], Timothy Brown[4], Douglas Caldwell[5], Edna DeVore[6], Edward Dunham[7], Thomas Gautier[8], John Geary[9], Ronald Gilliland[10], Alan Gould[11], Steve Howell[12], Jon Jenkins[13]

[1] *NASA Ames Research Center, Moffett Field, CA 94035, USA, William.J.Borucki@nasa.gov*
[2] *NASA Ames Research Center, Moffett Field, CA 94035, USA, David.G.Koch@nasa.gov*
[3] *University of California, Berkeley, CA 94720, USA,Gibor@astron.berkeley.edu*
[4] *High Altitude Observatory, NCAR, Boulder, CO 80307, USA,TimBrown@hao.ucar.edu*
[5] *SETI Institute, Mountain View, CA 94043, USA, dcaldwell@mail.arc.nasa.gov*
[6] *SETI Institute, Mountain View, CA 94043, USA, EdeVore@seti.org*
[7] *Lowell Observatory, Flagstaff, AZ 86001, USA, Dunham@lowell.edu*
[8] *Jet Propulsion Laboratory, Pasadena, CA 91109, USA, Thomas.N.Gautier@jpl.nasa.gov*
[9] *Harvard Smithsonian Center for Astrophysics, Harvard, MA 02138, USA, geary@cfa.harvard.edu*
[10] *Space Telescope Science Institute, Baltimore, MD 21218, USA, gillil@stsci.edu*
[11] *Lawrence Hall of Science, University of California, Berkeley, CA 94720, USA, AGould@uclink.berkeley.edu*
[12] *University of California, Riverside, CA 92521, USA, Steve.Howell@ucr.edu*
[13] *SETI Institute, Mountain View, CA 94043, USA, jjenkins@mail.arc.nasa.gov*

ABSTRACT

The *Kepler* Mission is a NASA Discovery-class mission designed to continuously monitor the brightness of 100,000 main sequence stars to detect the transit of Earth-size and larger planets. It is a wide field of view photometer with a Schmidt-type telescope and an array of 42 CCDs covering the 100 sq. degree field-of-view (FOV). It has a 0.95 m aperture and a 1.4 m primary and is designed to attain a photometric precision of 20 parts per million (ppm) for 12th magnitude solar-like stars for a 6.5-hour transit duration. It will continuously observe 100,000 main sequence stars from 9th to 15th magnitude in the Cygnus constellation for a period of four years with a cadence of 4 measurements per hour. The photometer is scheduled to be launched in 2007 into heliocentric orbit. A ground-based program to classify all 450,000 stars brighter than 15th magnitude in the FOV and to conduct a detailed examination of a subset of the stars that show planetary companions is also planned. Hundreds of Earth-size planets should be detected if they are common around solar-like stars. Ground-based spectrometric observations of those stars with planetary companions will be made to determine the dependences of the frequency and size of terrestrial planets on stellar characteristics such as type and metallicity. A null result would imply that terrestrial planets are rare.

1. INTRODUCTION

Small rocky planets at orbital distances from 0.9 to 1.2 AU are more likely to harbor life than the gas giant planets that are now being discovered with the Doppler-velocity technique. Technology based on transit photometry can find smaller, Earth-like planets that are a factor of several hundred times less massive than Jupiter-like planets. The *Kepler* Mission is designed to discover hundreds of Earth-size planets in and near the habitable zone (HZ) around a wide variety of stars. *Kepler* was selected as NASA Discovery Mission #10 in December 2001. A description of the mission and the expected science results are presented.

2. SCIENTIFIC GOALS

The general scientific goal of the *Kepler* Mission is to explore the structure and diversity of planetary systems with special emphasis on determining the frequency of Earth-size planets in the HZ of solar-like stars. This is achieved by surveying a large sample of stars to:

– Determine the frequency of 0.8 Earth-radii ($R_{\oplus}$) and larger planets in or near the habitable zone of a wide variety of spectral types of stars;

- Determine the distributions of sizes and orbital semi-major axes of these planets;
- Estimate the frequency of planets orbiting multiple-star systems;
- Determine the distributions of semi-major axis, eccentricity, albedo, size, mass, and density of short period giant planets;
- Identify additional members of each photometrically-discovered planetary system using complementary techniques; and
- Determine the properties of those stars that harbor planetary systems.

3. APPLICATION TO THE DARWIN/TPF MISSION

The *Kepler* Mission supports the Darrwin/Terrestrial Planet Finder (TPF) Mission by finding the association between the frequency and characteristics of terrestrial planets and stellar type and by determining the distributions of planet size and orbital semi-major axis. Since the *Kepler* FOV is along a galactic arm at the same galactocentric distance as the Sun, the stellar population sampled with *Kepler* is indistinguishable from the immediate solar neighborhood. A knowledge of the frequency of terrestrial planets and its dependence of stellar type as well as knowledge of the distribution of the semi-major axis provides the designers of the Darwin/TPF Mission with the information needed to select an instrument design with enough range to get a sufficient number of Earth-size planets in the HZ. Specification of the Darwin/TPF instrument aperture size and the required angular resolution are likely to be quite different if Earth-size planets are rare or plentiful. If the occurrence of Earths is found to be dependent on the absence of "hot jupiters" or the metallicity or spectral type of star, then promising targets can be selected with little time lost on unproductive targets.

4. PHOTOMETER AND SPACECRAFT DESCRIPTION

The instrument is a wide FOV differential photometer with a 100 square degree field of view that continuously and simultaneously monitors the brightness of 100,000 main-sequence stars with sufficient precision to detect transits by Earth-size planets orbiting G2 dwarfs. The brightness range of target stars is from visual magnitude 9 through 15. The photometer is based on a modified Schmidt telescope design that includes field flatteners near the focal plane. Fig. 1 is a schematic diagram of the photometer. The corrector has a clear aperture of 0.95 m with a 1.4 m diameter F/1 primary. This aperture is sufficient to reduce the Poisson noise to the level required to obtain a 4σ detection for a single transit from an Earth-size planet transiting a 12th magnitude G2 dwarf. The focal plane is composed of forty-two 1024x2200 backside-illuminated CCDs with 27 μm pixels
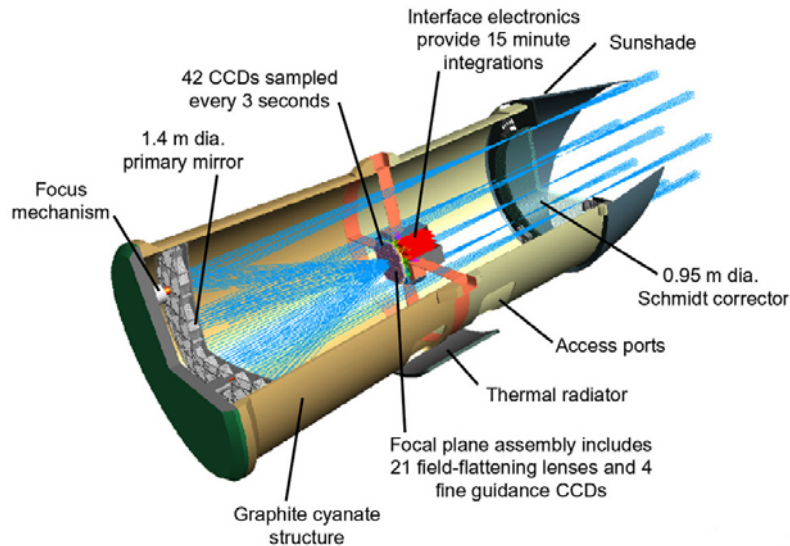

Fig. 1. Schematic diagram of *Kepler* photometer.

The detector focal plane is at prime focus and is cooled by heat pipes that carry the heat out to a radiator in the shadow of the spacecraft. The low-level electronics are placed immediately

behind the focal plane. A four-vane spider supports the focal plane and its electronics and contains the power- and signal-cables and the heat pipes.

The spacecraft bus encloses the base of the photometer supports the solar panels for power and the communication, navigation, and power equipment. Several antennas with different frequency coverage and gain patterns are available for uplink commanding and for data downlink. A steerable high-gain antenna operating at Ka band is used for high-speed data transfer to the Deep Space Network (DSN). It is

the only articulated component other than the ejectable cover. Approximately 1 GByte/day of data are recorded and then transferred to the ground every few days when contact is made with the DSN. The spacecraft provides very stable pointing using four fine guidance sensors mounted in the photometer focal plane. Small thrusters are used to desaturate the momentum wheels. Sufficient expendables are carried to extend the mission to six years.

Both the instrument and the spacecraft are being built by the Ball Aerospace and Technology Corporation (BATC) in Boulder, Colorado.
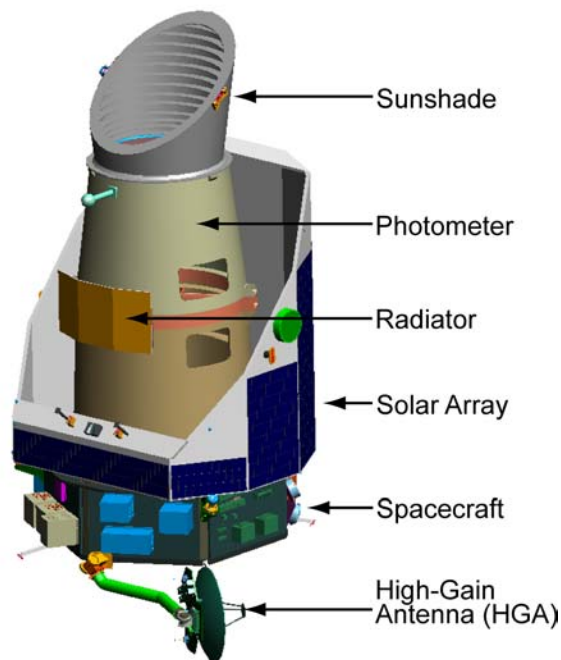

Fig. 2. Integrated spacecraft and photometer.

5. SCIENTIFIC APPROACH

To achieve the required photometric precision to find terrestrial-size planets, the photometer and the data analysis system must be designed to detect the very small changes in stellar flux that accompany the transits. In particular, the variability of the star, on time scales different than that of the transits, is not of interest. Sharp images of the star field are not helpful because the PSF must be over-sampled and because a broad image profile reduces the sensitivity to

image motion. This provides the best estimates of image centroids that are used to reduce the systematic error due to image drift. The *Kepler* Mission approach is best described as "differential relative photometry". In this approach;

–   Target stars are always measured relative to the ensemble of similar stars on the same part of the same CCD and read out by the same amplifier.

3

- Only the time change of the ratio of the target star to the ensemble is of interest. Only decreases from a trend line based on a few times the transit duration are relevant (long-term stability of the trend is not required).
- Target star and ensemble stars are read out every three seconds to avoid drift and saturation
- A broad PSF is used to avoid saturated pixels and to allow image centroids to be tracked and used to reduce systematic errors.
- Correction for systematic errors is critical [7].

Photometry is not done on the spacecraft. Instead, all of the pixels associated with each star image are telemetered to the ground for analysis. This choice allows many different approaches to be used to reduce systematic errors.

The spacecraft is placed in an Earth-trailing heliocentric orbit by a Delta II 2925-10L launch vehicle. The heliocentric orbit provides a benign thermal environment to maintain photometric precision. It also allows continuous viewing of a single FOV for the entire mission without the Sun, Earth or Moon obtruding. Only a single FOV is monitored during the entire mission to avoid missing transits.

A pattern of at least three transits that shows that the orbital period repeats to a precision of at least 10 ppm and that shows at least a 7σ detection is required to validate any discovery. The mission lifetime of four years allows four transits to be observed so that 8σ detections can be obtained. A detection threshold of 7σ is required to avoid false positives due to random noise. Planetary signatures exhibiting mean detection statistics of 7σ will be recognized 50% of the time. The recognition rate for planets exhibiting 8σ detection statistics increases to 84%.

Classical signal detection algorithms that whiten the stellar noise, fold the data to superimpose multiple transits, and apply matched filters are employed to search for the transit patterns down to the statistical noise limit [6]. From measurements of the period, change in brightness and known stellar type, the planetary size, the semi-major axis and the characteristic temperature of the planet can be determined.

Only data from pixels illuminated by pre-selected target stars are saved for transmission to Earth. Data for each pixel are co-added onboard to produce one brightness measurement per pixel per 15-minute integration. Data for target stars that are monitored for p-mode analysis are measured at a cadence of once per minute.

6. SELECTION OF TARGET STARS AND FIELD OF VIEW

Approximately 100,000 target stars must be monitored to get a statistically meaningful estimate of the frequency of terrestrial planets in the HZ of solar-like stars. A FOV centered on a galactic longitude of 70 deg and latitude of + 6 deg satisfies both the constraint of a 55 degree sun-avoidance angle and provides a very rich star field. This FOV falls within the Cygnus constellation and results in looking along the Orion spiral arm. (Fig. 3.) In the 100 sq degree *Kepler* FOV, there are approximately 450,000 stars brighter than 15th magnitude. Studies are underway to determine the most efficient way of classifying such a large number of stars and choosing the most appropriate 100,000 as targets. The current approach is to use a wide FOV ground-based telescopes with an appropriate color-filter system to identify both the luminosity class and spectral types and thereby enable the elimination giants and early spectral types from the target list.

FIELD OF VIEW IN CYGNUS
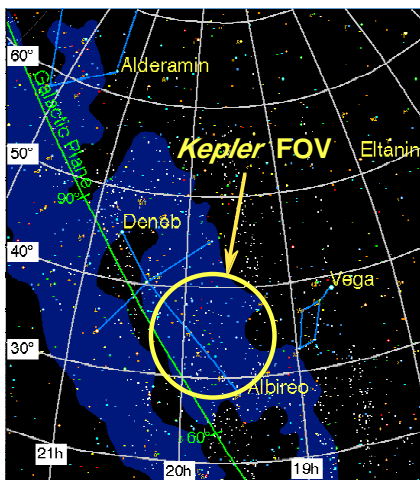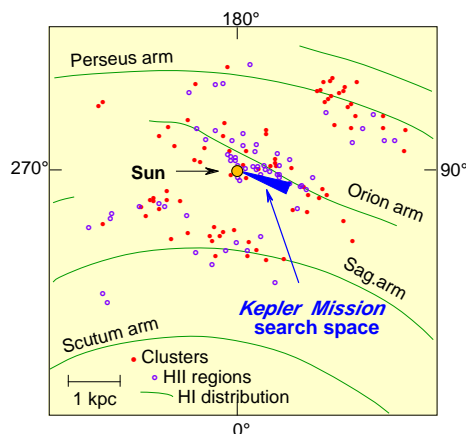

EXTENDED SOLAR NEIGHBORHOOD

Fig 3. *Kepler* FOV in the Cygnus constellation, looking along the Orion spiral arm.

If 100,000 dwarf stars of spectral type B through M are monitored and if every such star has such a planet, then only about 500 planets will be discovered because the geometrical probability that the planets' orbit will be aligned well enough to show transits is only about 0.5%.
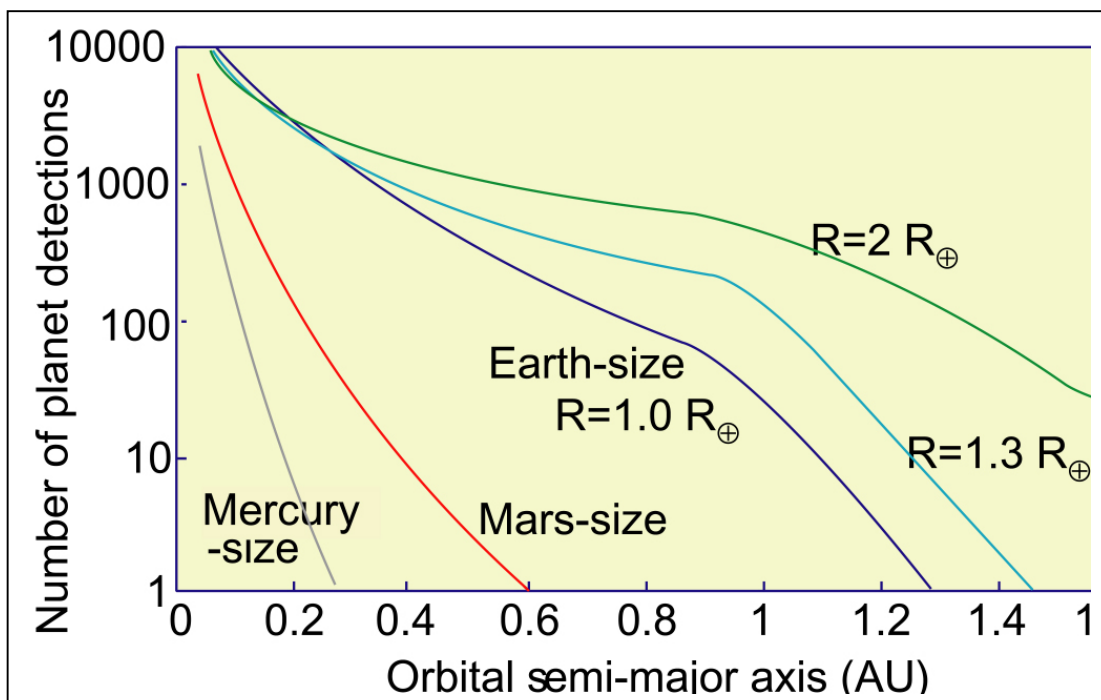

Fig. 4. Trace of the number of planets expected to be detected if all stars have one planet at the position indicated. Note the high sensitivity of the results to the planet diameter and the orbital semi-major axis.

7. EXPECTED RESULTS

After the mission ends, the results can be summarized as graphs analogous to those shown in Fig 4. Because both the size and mass of the stars that are found to have planets will be determined by follow-up observations, the size of the planets and their orbital semi-major axes can be determined. If most stars have planets approximately the size of the Earth (0.9 < $R_\oplus$ < 1.2,) for example, then we should find data points along the curve marked "Earth-size". At distances near 1 AU (0.8 < a < 1.2 AU), we expect approximately 25 planets. If most stars have two such planets (like Earth and Venus) in that region, then there will be a point showing that 50 planets were detected there. If stars often have planets 30% larger, then because such planets are more readily detected, then points along the curve marked "1.3 $R_\oplus$" will recorded and a data point for 200 planets will be plotted for a semi-major axis near 1 AU. Planets twice the radius of the Earth (i.e., approximately 10 times the mass of the Earth) are readily detected even for large or dim stars so about 600 planets should be detected near 1 AU.

These values are based upon a realistic distribution of spectral types for a magnitude-limited survey. For a limiting visual magnitude of 14, about 50% of the stars will be early types that are too big to produce a SNR>7 for an Earth-size planet and/or too massive to produce a pattern with at least three transits during the four-year mission duration. Studies are underway to find somewhat dimmer stars of later spectral type that would have sufficiently large signals to overcome the increased photon shot noise. If there is an efficient way to find such stars, they will replace many of the brighter-but-earlier–spectral-type stars. This change could nearly double the number of small planets found with large values of semi-major axes.

As the semi-major axis decreases, the expected number of discoveries rises very rapidly, even on a log plot. This occurs for two reasons. First, the probability of a detection increases as the inverse of the orbital radius and second, the number of transits that occur during the mission lifetime increases. The detectability of transit patterns rapidly increase with the signal-to-noise ratio (SNR) and the SNR increases with the square root of the number of transits. At the value of the semi-major axis found for the "hot Jupiters" detected by the Doppler velocity technique, i.e., ~0.05 AU, tens of thousands of planets should be found if they are common orbiting solar-like stars. Even if the planets are as small as Mars or Mercury, the number of transits that occur in such tight orbits during a four year mission will be so large (~ 400) that small planets should be found in profusion.

Of course, there is no reason to expect that all solar-like stars have planets and therefore the actual data points are likely to fall well below the curves shown in the Fig. 4. Nevertheless, if planetary frequencies are as high as 1%, many terrestrial-size planets should be found.

After two years of operation, the *Kepler* Mission should provide a good estimate of the frequency of Earth-size planets with orbital periods as long as six months. Once the mission length reaches four years, a good estimate of that frequency will be obtained for planets in the HZ of solar-like stars. However, because not all stars are expected to have Earth-size planets in the HZ, and because the HZ could extend to the orbit of Mars [3,8], it is worth considering the benefit of an extension of the mission from the planned four years to six years. The uppermost curves in Fig. 5 show the dependence of the expected number of discoveries of Earth-size planets on the mission duration and semi-major axis. Clearly, the fractional increase in planet discoveries is dramatic for semi-major axes of 1 AU and larger. The increased mission duration raises the number of expected detections by a factor of two at 1 AU and a factor of 3.5 at 2 AU. If Earth-size planets are rare, this increase could be very helpful in providing an estimate of the number of stars that must be observed by the Darwin/TPF mission if it is to fulfill its goal of determining the atmospheric composition of Earth-size planets in the HZ of solar-like stars.

Planets as small as Mars might be habitable if they are well placed in the HZ. Such planets can be detected if the stars are smaller than the Sun or if the planets are in short period orbits. K stars are smaller and cooler than the Sun and have their HZ at distances of 0.2 to 1.0 AU. Hence the orbital periods in the HZ are measured in months and the total SNR of Mars-size planets is

sufficient for valid detections. Again note the dramatic increase in the discovery result as the mission duration increases. At a semi-major axis of 0.5 AU, no planets are expected if the mission duration is 3 years. Two are expected for a 4-year mission and six are expected when the mission duration is increased to six years. It is clear from the lower curves, that knowledge of the lower end of the size distribution of rocky planets will be significantly improved by increasing the mission duration to six years.

Number of Mars- and Earth-sized Planets vs Duration of Observations
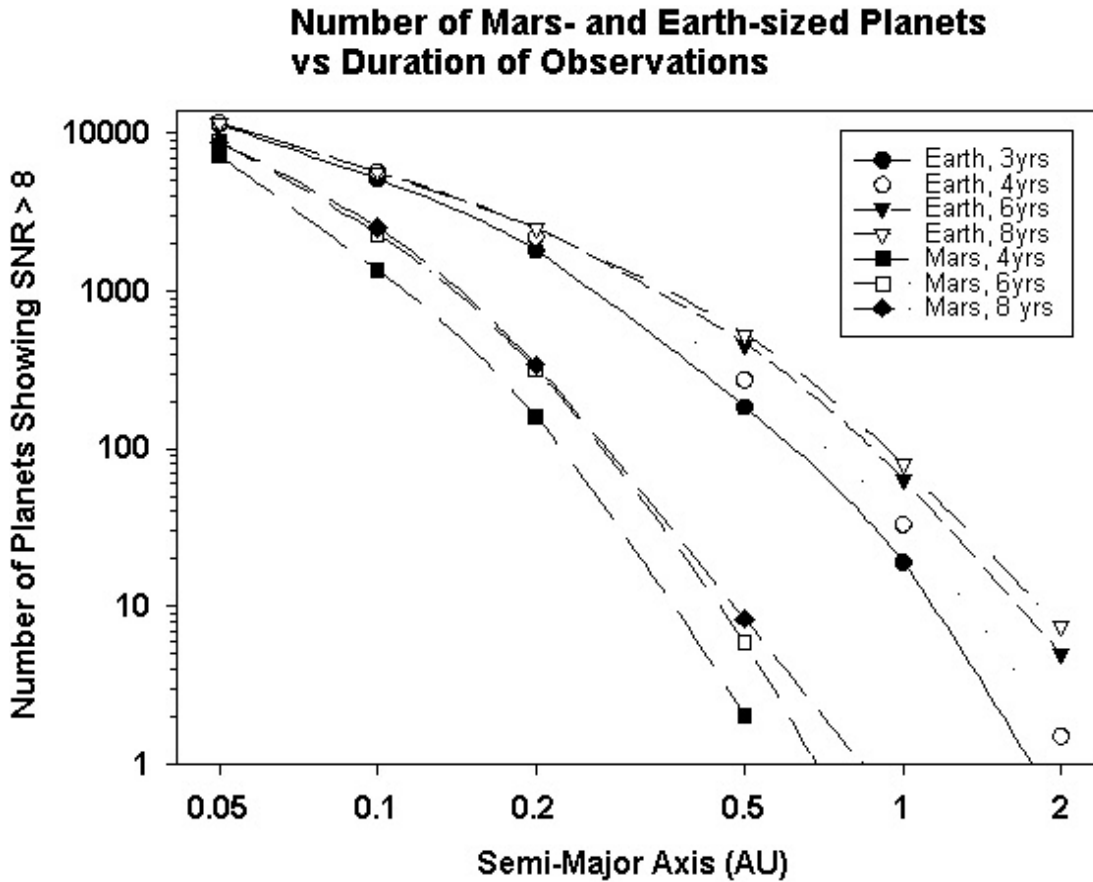

Fig. 5. Expected number of planets detected versus mission duration and semi-major axis. The upper curves are for Earth-size planets while the lower curves are for Mars-size planets.

Giant planets, like 51 Pegasi, with orbits of less than seven days are also detected by the periodic phase modulation of their reflected light without requiring a transit [2]. For the short-period giant planets that do transit, the planetary albedo can be calculated. Information on the scattering properties of the planet's atmosphere can also be derived [8,10,11].

Ground-based Doppler spectroscopy and/or space-based astrometry with SIM can be used to measure the planetary masses, if they are jovian or larger, and to distinguish between a planet and a brown dwarf. These complementary methods can also detect additional massive companions in the systems to better define the structure of each planetary system. The density of any giant planet detected by both photometry and either of the other methods can be calculated. Determination of the planet size, mass, semi-major axis, and stellar properties provides the properties needed for the validation and development of theoretical models of planetary structure.

White dwarf stars are about the size of the Earth and might be expected to produce a transit signal of similar magnitude. However, because of the gravitational lensing caused by their large-but-compact mass, the transits actually result in an increase in brightness [9] and are thereby readily distinguished from those of a planet.

8. INFLUENCE OF STELLAR VARIABILITY ON THE DETECTABILITY OF TRANSIT SIGNALS

Stellar variability sets the limit to the minimum size of planet that can be detected. It reduces the signal detectability in two important ways;

−   The variability introduces noise into the detection passband and thereby reduces the signal to noise ratio (SNR) and thus the statistical significance of transits.
−   Because the flux of every target star is ratioed to the fluxes of many surrounding stars to reject common-mode instrument

noise, variability of the stars used in the normalization introduces noise into the target star signal.

The second concern can be alleviated by measuring the variability of each star relative to an ensemble of others and then iteratively removing the noisiest from the list of comparison standards. To mitigate the effects of the first concern, stars must be chosen that have low variability.

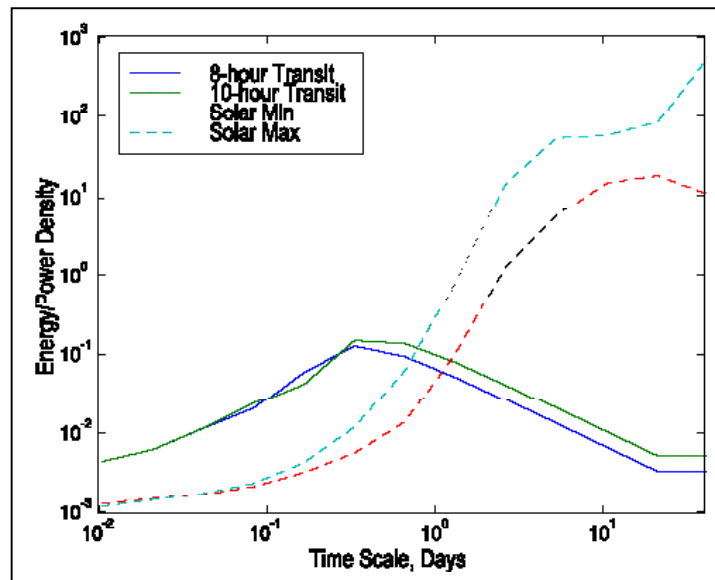Power spectra for the Sun at solar maximum and minimum are shown in Fig. 6.

Fig. 6. Power spectra of solar variability at Solar Maximum and Minimum. Also shown are energy spectra of 8-hr and 10-hr transits.

Also shown are the energy spectra for transits with 8- and 10-hour durations. It's clear that most of the solar variability is at periods substantially longer than those associated with planetary transits. In particular, the Sun's variability for samples with duration similar to that for transits is about 10 ppm. For stars rotating more rapidly than the Sun, the power spectrum will increase in amplitude and move to shorter periods thus increasing the noise in the detection passband.

Stellar variability in late-type main sequence stars is usually associated with the interplay of the convective layer and the internal magnetic

field. Because the depth of the convective layer is a function of the spectral class of the star and because the activity level is higher when the star is rotating rapidly, the variability of solar-like main sequence stars is related to both their spectral class and rotation rate. Further, because the rotation rate decreases with age, the age of a star is an important variable. Thus we expect that the factors that influence the variability of target stars are age and spectral type.

The age and rotation rate of the Sun are approximately 5 Gyr and 27 days, respectively. The age of the galaxy is about 12 Gyr and about

2/3 of the stars are older than the Sun and are expected to be at least as quiet as the Sun. That extrapolation cannot be verified by examining the actual photometric variability of solar-like stars because no star other than the Sun has been measured to the requisite precision. However, the R'_{HK} index is believed to be well correlated to stellar variability. It is based on the spectral line profile of the Calcium H and K lines and is readily measured with ground-based telescopes.

Fig. **7.** shows measurements of the R'_{HK} index for a variety of spectral types. As can be seen from Fig. **7.** , about 70% of the stars are found to have the index at least as low as that of the Sun. Hence we plan to choose approximately 130,000 late type dwarfs to monitor during the first year of observations and then gradually eliminate those that are too variable to find Earth-size planets. This is necessary because the telemetry rate will decrease as the spacecraft recedes from the Earth.
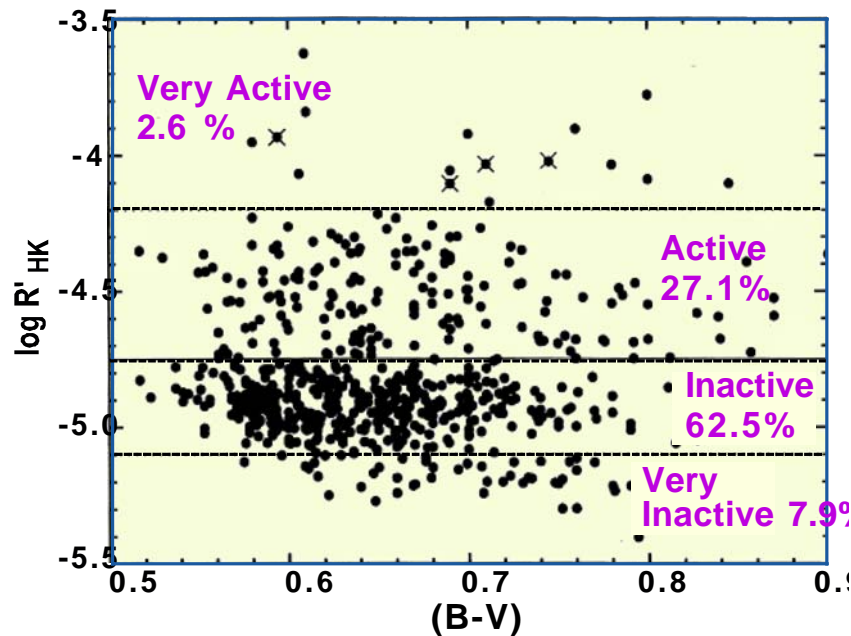

Figure 7. Activity indicator R'_{HK} versus stellar spectral type [4]. The Sun lies in the middle of the inactive region. Its value of R'_{HK} varies throughout the bin during the solar activity cycle. Note that most stars are less active than the Sun.

Although most solar-like stars are expected to have stellar activity levels no higher than that of the Sun, planets can still be found around stars with higher activity levels if the size of the planets are somewhat larger than the Earth of if they are found in the habitable zone of later spectral types. Planets in the HZ of K dwarfs have orbital periods of a few months and therefore would show about 16 transits during a four-year mission. Fig. 8. shows the minimum size planet required to produce an 8σ detection versus the amplitude of the stellar variability assuming that the frequency distribution of the stellar noise is the same as that of the Sun. The upper curve shows that the amplitude of the stellar noise would need to be at least eight times that of the Sun before it would prevent planets slightly larger than twice the radius of the Earth from being detected. For planets showing 16 transits, planets as small as 1.4 times the radius of the Earth would still be detectable.
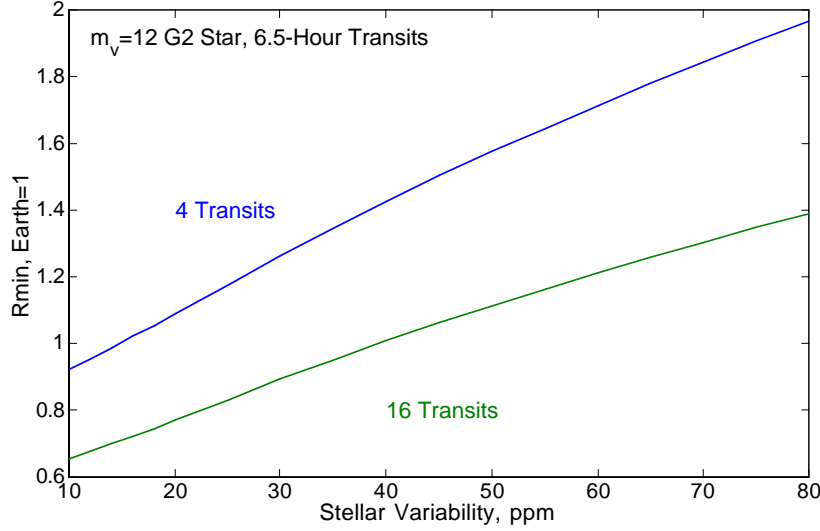
Figure 8. Effect of increased stellar variability on the minimum size planet that can be detected with 8σ.

9. INTERPLAY OF NOISE FROM STELLAR VARIABILITY, POISSON VARIATIONS, AND THE INSTRUMENT

As described earlier, it is important to find planets with a size sufficient to produce 8σ detections with three or more transits. Eq. 1. shows the relationship (greatly simplified) to the signal to noise ratio (SNR) as a function of ratio of the area of the planet to area of the star (A_p/A_*), number of transits (N_{tran}), and the noise due to stellar variability (v), Poisson noise in the stellar flux (F), and instrument noise (i);

$$SNR = (N_{tran})^{1/2} (A_p/A_*) / [(i^2 + v^2) + 1/F]^{1/2} \quad (1)$$

An examination of this equation shows that for very bright stars where 1/F is small and when the stellar variability dominates the instrument noise, the SNR is dominated by the stellar variability. The opposite is true for dim stars where 1/F is large and the SNR is dominated by the shot noise in the stellar flux. Table 1 presents calculated noise values for *Kepler* instrument. For all entries in this table, a stellar variability of 10

ppm is assumed. Note that at 14th magnitude, although the effect of stellar variability is negligible, instrument noise also makes a substantial contribution. Such large values of instrument noise warn that assuming shot-noise-limited performance is unwarranted. It is also clear that for stars 14th magnitude and dimmer, detectable planets must be somewhat larger than the diameter of the Earth if they are to be reliably detected orbiting G2 dwarfs.

Table 1. Comparison of Signal and Noise and Minimum Size Planet that Produces an 8σ Signal			
Visual magnitude	9	12	14
Stellar signal (photo electrons)	9x10^10	6x10^9	9x10^8
Stellar shot noise (ppm)	3.3	13	35
Instrument noise (ppm)	1.7	7	30
Solar variability (ppm)	10	10	10
Relative signal for Earth transit across the Sun (ppm)	84	84	84
SNR for 4 transits	15	9	3.5
Minimum detectable planet radius (Earth=1) at 8σ	0.7	0.9	1.5

10. VALIDATION OF PLANET DETECTIONS

Before a candidate detection can be considered to be a validated planet and the information released to the public, a rigorous validation process must be executed to ensure that it is not due to some other phenomenon [3]. Public release of false positives would ultimately discredit any mission results. Therefore to be considered a reliable detection the candidate planet detection must meet several requirements.

- The total SNR of the superimposed transits must exceed 7σ. This requirement prevents false positives produced by statistical noise when 8×10^{11} statistical tests are carried out on 10^5 stars for orbital periods from 1 to 700 days.
- At least three transits must be observed that demonstrate a period constant to 10 ppm. This test is independent of the previous test and demonstrates the presence of a highly periodic process. It essentially rules out mistaking stellar phenomenon for transits.
- The duration, depth, and shape of the light curve must be consistent. The duration must be consistent with Kepler's laws based on the orbital period. The depth must be consistent over all transits. A weaker requirement is that the shape must be consistent with a "U" shape of a planetary transit rather than a "V" shape of a grazing eclipse of a binary star. Clearly, low-amplitude transits are likely to be too noisy to make this distinction.
- The position of the centroid of the target star determined outside of the transits must be the same as that of the differential transit signal. If there is a significant change in position, the cause of the signal is likely to be an eclipsing star in the background.
- Radial velocity measurements must be conducted to demonstrate that the target star is not a grazing eclipsing binary.
- High precision radial velocity measurements must be made to measure the mass of the companion or provide an upper limit that is consistent with that of a small planet.
- High spatial resolution measurements must be made of the area immediately surrounding the target star to demonstrate that there is no background star in the aperture capable of producing a false positive signal.

It is also possible that future instrumentation on HST and JWST will have sufficient precision to detect the color changes during the transit. A measured color change consistent with the differential limb darkening expected of the target star [1] would strengthen the validation. A shape or depth substantially different than expected would point to the possibility of a very close background star that differed in spectral type.

11. DATA RELEASE POLICY

To avoid publication of false positives, the series of ground-based observations described above must be made and analyzed to validate the discovery before any announcements are made. It is expected that several months will be required to obtain telescope time on suitable ground-based telescopes and make the observations with the usual time lost due to bad weather and to the limited seasonal observability of the FOV. Hence the data will not be released until several months have passed from the time that at least three transits with a combined SNR $>7\sigma$ have been detected.

For planets with short orbital periods, three or more transits will be seen within the first weeks and months of operation. Release of these data are expected by the end of the first year of operation. Shortly thereafter, data and light curves for those stars found to be too variable to be useful targets will also be released.

When data are released, both original calibrated data for each target and the light curves generated by ensemble photometry will be provided so that all interested members of the scientific community can independently assess the reliability of the results.

12. EDUCATION AND PUBLIC OUTREACH PROGRAMS

Bringing the science and the excitement of space projects to students and the general public is a major goal of all NASA efforts. To further this goal, the *Kepler* Mission includes two institutions that produce high quality educational materials and have high impact in education nationally: Lawrence Hall of Science (University

of California) and SETI Institute. Formal education contributions will include Great Explorations in Math and Science (GEMS) teacher guides in math and science for grades K through 8, Full Option Science System (FOSS) teacher workshops for middle schools, and addition of a *Kepler*-science module in the Hands-On Universe high school curriculum. For informal science education, *Kepler* is developing museum exhibits on planet-finding with Space Science Institute (SSI), and programs for small and medium-size planetariums serving both school and public audiences. *Kepler* will fund the creation of public radio broadcasts through STARDATE and a video program suitable for public broadcast. To enhance participation by the public, predictions of the large-amplitude transits by giant planets will be distributed via the *Kepler* website so that amateur astronomers and institutions with CCD-equipped facilities can observe planetary transits. To increase the use of CCD technology, several CCD cameras will be supplied to minority colleges that already have telescopes. Training and support will be provided to the college faculty in photometric observing techniques and data analysis methods required for high precision photometry in discovery and observation of planetary transits.

12. MISSION STATUS

The *Kepler* Mission was chosen as Discovery Mission #10 in December of 2001 and funds to proceed were received to start the Phase B work in early 2002. An outline of the mission schedule is shown in Fig. 9. In the summer of 2002, a new management team from the Jet Propulsion Lab was chosen to provide overall mission management. The JPL team members have been smoothly integrated with those at Ames and BATC. Their addition greatly strengthens the *Kepler* Mission by providing great depth in mission management and engineering.
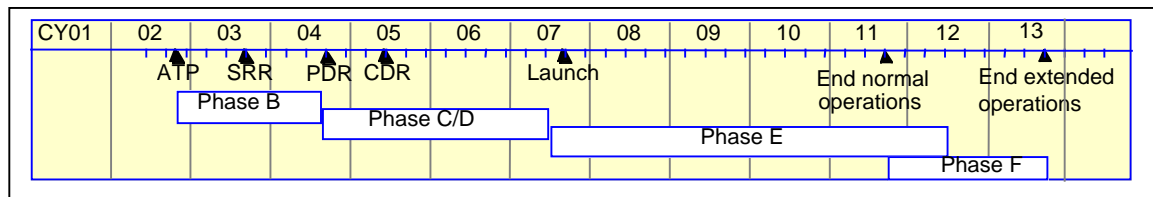

Fig. 9. Outline of *Kepler* Mission schedule.

In the fall of 2002, 30 CCD detectors were ordered from each of two vendors. This "twin buy" approach insures that the large number of detectors required for the *Kepler* focal plane will be available even if one of the two vendors runs into difficulties, since both vendors have options for delivering all 60 flight CCDs. All mechanical grade detectors have now been received and tested. Delivery of the evaluation grade detectors has begun.

The Brashear Corporation won the competition for building both the 0.95m corrector and the 1.4 m primary for the Schmidt optics. Delivery is expected in 2005. Negotiations for other long-lead items are in progress.

In summary, the *Kepler* Mission is on schedule for an October 2007 launch.

13. REFERENCES:

1. Borucki, W. J., and A. L. Summers. The photometric method of detecting other planetary systems. Icarus **58**, 121-134, 1984.

2. Borucki, W. J., D. G. Koch, E. W. Dunham, and J. M. Jenkins. The Kepler Mission: A mission to determine the frequency of inner planets near the habitable zone for a wide range of stars. Planets Beyond the Solar System and the Next Generation of Space Missions. ASP Conference Series **Vol. 119**, 153-173, 1997.

3. Franck, S., A. Block, W. von Bloh, C. Bounama, A. J. Schellnhuber, and Y Svirezhev. Habitable zone for Earh-like planets in the solar system. Plan.& Space Sci. **48**, 1099-1105, 2000.

4. Henry, T.J., D.R. Soderblom, R.A. Donahue, and S.L. Baliunas. AJ 111, 439, 1966.

5. Jenkins, J. M. The impact of stellar variability on the detectability of transiting terrestrial planets. ApJ **575**, 493-501, 2002.

6. Jenkins, J. M., D. A. Caldwell, and W. J. Borucki. Some test to establish confidence in planets discovered by transit photometry. ApJ **564**, 495-507, 2002.

7. Kasting, J. F., D. P. Whitmire, and R. T. Reynolds. Icarus **101**, 108, 1993.

8. Marley M. S., C. Gelino, D. Stephens, J. I. Lunine and R. Freedman. Reflected spectra and albedos of extrasolar giant planets. I. Clear and cloudy atmospheres. ApJ. **513**, 879-893, 1999.

9. Sahu, K. C. and R. L.Gilliland. Near-field microlensing and its effects on stellar transit observations by *Kepler*. ApJ. **584**, 1042-1052, 2003.

10. Seager, S. , B. A. Whitney, and D. D. Sasselov. Photometric light curves and polarization of close-in extrasolar giant planets. ApJ. **540**, 504-520, 2000.

11. Sudarsky, D., A. Burrows, and P. Pinto. Albedo and reflection spectra of extrasolar giant planets. ApJ. **538**, 885-903, 2000.